Scattering RT in a 3D spherical atmosphere at mm / sub-mm wavelengths with ARTS

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Outline

Motivation

- To simulate measurements by space-borne passive mm-submm instruments in the presence of clouds.
  - Aura-MLS, AMSU, Odin-SMR, JEM/SMILES, ...
- RT model requirements
  - Thermal atmospheric source (solar negligible)
  - Scattering -> 3D geometry, polarization
  - Limb Sounding -> spherical geometry

Atmospheric Radiative Transfer System - ARTS

- Stable version ARTS 1.0.x
  - Clear Sky only (1-D spherical shell)
  - spectroscopy, ray-tracing, clear-sky RT, sensor modelling
- Development version ARTS 1.1.x (pre 2.0)
  - Scattering
  - 3D geometry
  - Polarized RT
- Some details
  - developed in C++
  - distributed with user guide, examples, and test cases
  - Wiki - http://www.sat.uni-bremen.de/arts/wiki
  - ARTS distribution freely available from http://www.sat.uni-bremen.de/arts/

ARTS Scattering Modules

ARTS-1.1.x has two modules capable of 3D polarized radiative transfer:

- ARTS-DOIT *Emde et al., J. Geophys. Res., 109(D24), D24207, 2004*
  - 1D or 3D Discrete Ordinates Iterative type model. Has similarities with SHDOM and VDOM, except extended to polarized RT and spherical geometry.
  - Solves the radiation field for the whole scattering domain (i.e. all angles, all grid points)
- ARTS-MC *Davis et al., IEEE T. Geosci. Remote, 43(6), 1096-1101, 2005*
  - **Reversed** Monte Carlo RT. Similar to Backward Forward Monte Carlo model by Liu et al, but uses importance sampling to properly account for polarization
  - Only solves for given position and viewing direction.

We have come to realise that ARTS-DOIT is **NOT** practical for realistic 3D cases. The rest of the talk covers ARTS-MC

Why Reversed Monte Carlo?

- All computational effort is dedicated to calculating the Stokes vector at the location of interest and in the direction of interest.
- CPU cost scales more slowly than other methods with grid size. Large or detailed 3D scenarios are not a problem
- Optically thick media are no problem.
- Simple concept -> rapid development.
- Why not DOM?
    - Big CPU cost in calculating unwanted radiances
    - Cost scales badly with grid size
    - Not well suited to spherical geometry
    - Limb sounding requires a prohibitively fine angle grid.
- Why not forward MC?
    - big source/small target
    - optically thick medium makes this worse

ARTS-MC: Algorithm Description

We are solving the Vector Radiative Transfer Equation

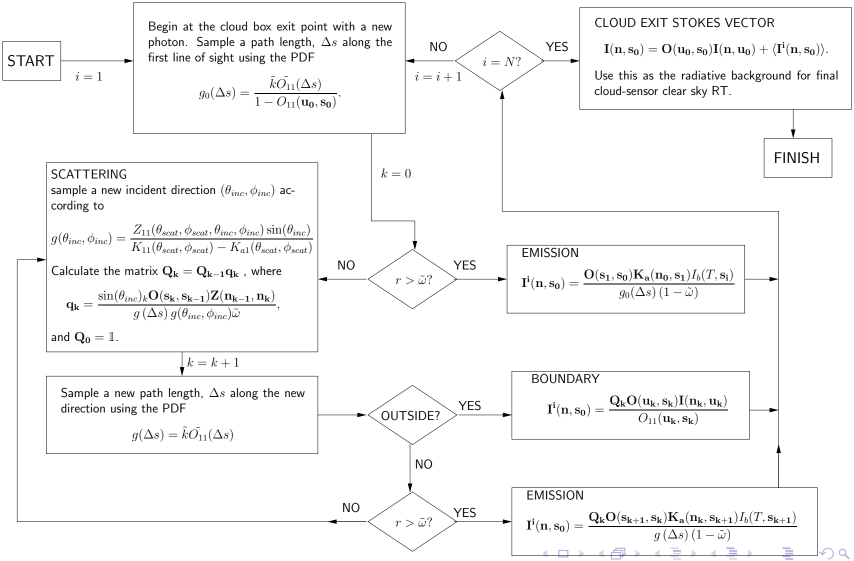
$$\frac{d\mathbf{I}(\mathbf{n})}{ds} = -\mathbf{K}(\mathbf{n})\mathbf{I}(\mathbf{n}) + \mathbf{K_a}(\mathbf{n})I_b(T) + \int_{4\pi} \mathbf{Z}(\mathbf{n},\mathbf{n}')\mathbf{I}(\mathbf{n}')d\mathbf{n}' \qquad (1)$$

, where $\mathbf{I} = [I, Q, U, V]^T$. We solve this by applying Monte Carlo integration with importance sampling ...

$$\int f dV = \int \frac{f}{g} g dV \approx \left\langle \frac{f}{g} \right\rangle \pm \sqrt{\frac{\langle f^2/g^2\rangle - \langle f/g\rangle^2}{N}} \qquad (2)$$

...to an integral form of the VRTE

$$\mathbf{I}(\mathbf{n},\mathbf{s_0}) = \mathbf{O}(\mathbf{u_0},\mathbf{s_0})\mathbf{I}(\mathbf{n},\mathbf{u_0}) + \int_{u_0}^{s_0} \mathbf{O}(\mathbf{s}',\mathbf{s_0}) \left(\mathbf{K_a}(\mathbf{n})I_b(T) + \int_{4\pi} \mathbf{Z}(\mathbf{n},\mathbf{n}')\mathbf{I}(\mathbf{n}')d\mathbf{n}'\right) ds' \qquad (3)$$


START
$i = 1$
Begin at the cloud box exit point with a new photon. Sample a path length, Δs along the first line of sight using the PDF
$g_0(\Delta s) = \frac{\tilde{k}\tilde{O}_{11}(\Delta s)}{1 - O_{11}(\mathbf{u_0}, \mathbf{s_0})}$.
NO
$i = N?$
$i = i + 1$
YES
CLOUD EXIT STOKES VECTOR
$\mathbf{I}(\mathbf{n}, \mathbf{s_0}) = \mathbf{O}(\mathbf{u_0}, \mathbf{s_0})\mathbf{I}(\mathbf{n}, \mathbf{u_0}) + \langle \mathbf{I^i}(\mathbf{n}, \mathbf{s_0})\rangle$.
Use this as the radiative background for final cloud-sensor clear sky RT.
FINISH
$k = 0$
SCATTERING
sample a new incident direction $(\theta_{inc}, \phi_{inc})$ according to
$g(\theta_{inc}, \phi_{inc}) = \frac{Z_{11}(\theta_{scat}, \phi_{scat}, \theta_{inc}, \phi_{inc}) \sin(\theta_{inc})}{K_{11}(\theta_{scat}, \phi_{scat}) - K_{a1}(\theta_{scat}, \phi_{scat})}$
Calculate the matrix $\mathbf{Q_k} = \mathbf{Q_{k-1}}\mathbf{q_k}$, where
$\mathbf{q_k} = \frac{\sin(\theta_{inc})_k \mathbf{O}(\mathbf{s_k}, \mathbf{s_{k-1}})\mathbf{Z}(\mathbf{n_{k-1}}, \mathbf{n_k})}{g\,(\Delta s)\, g(\theta_{inc}, \phi_{inc})\tilde{\omega}}$,
and $\mathbf{Q_0} = \mathbb{1}$.
NO
$r > \tilde{\omega}?$
YES
EMISSION
$\mathbf{I^i}(\mathbf{n}, \mathbf{s_0}) = \frac{\mathbf{O}(\mathbf{s_1}, \mathbf{s_0})\mathbf{K_a}(\mathbf{n_0}, \mathbf{s_1}) I_b(T, \mathbf{s_i})}{g_0(\Delta s)\,(1 - \tilde{\omega})}$
$k = k + 1$
Sample a new path length, Δs along the new direction using the PDF
$g(\Delta s) = \tilde{k}\tilde{O}_{11}(\Delta s)$
OUTSIDE?
YES
BOUNDARY
$\mathbf{I^i}(\mathbf{n}, \mathbf{s_0}) = \frac{\mathbf{Q_k}\mathbf{O}(\mathbf{u_k}, \mathbf{s_k})\mathbf{I}(\mathbf{n_k}, \mathbf{u_k})}{O_{11}(\mathbf{u_k}, \mathbf{s_k})}$
NO
NO
$r > \tilde{\omega}?$
YES
EMISSION
$\mathbf{I^i}(\mathbf{n}, \mathbf{s_0}) = \frac{\mathbf{Q_k}\mathbf{O}(\mathbf{s_{k+1}}, \mathbf{s_k})\mathbf{K_a}(\mathbf{n_k}, \mathbf{s_{k+1}}) I_b(T, \mathbf{s_{k+1}})}{g\,(\Delta s)\,(1 - \tilde{\omega})}$

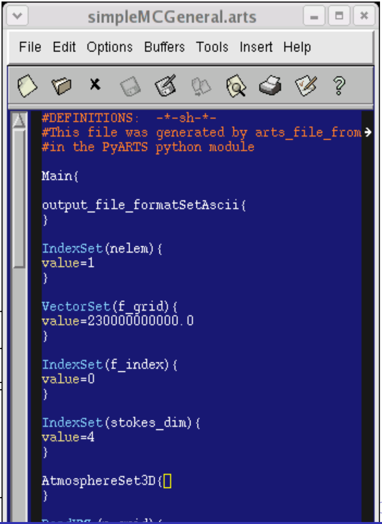
Implementation

- Atmospheric fields defined on Pressure, latitude, longitude grids
- Data I/O through ARTS specific XML file format (ascii or binary)
- Scattering properties calculated externally (PyARTS/T-matrix)
- scattering calculations confined to a subset of the atmosphere - cloudbox
- Currently there are two ARTS-MC Workspace Methods (I will describe WSMs later)
    - ScatteringMonteCarlo - as described in my paper; pencil beam only, blackbody surface.
    - MCGeneral - small changes to allow for surface reflection and 2D antenna functions

Control File Example

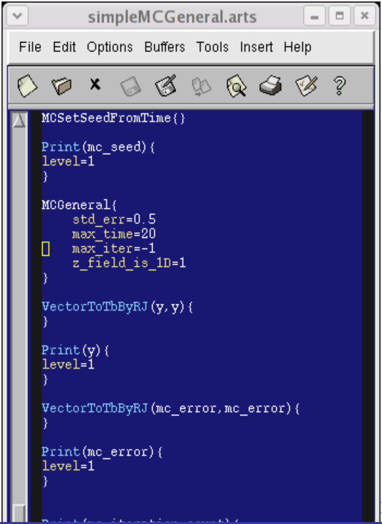
- Control files specify a sequence of commands in the ARTS “workspace”
- ARTS has predefined workspace variables. These can be listed by “arts -w all”, and a description retrieved by “arts -d varname”, e.g.

```
[cory@sundog bin]$ arts -d f_grid

*---------------------------------------------------------------
Workspace variable = f_grid
---------------------------------------------------------------

The frequency grid for monochromatic pencil beam calculati

Usage:      Set by the user.

Unit:       Hz

---------------------------------------------------------------
Group = Vector
```



Control File Example

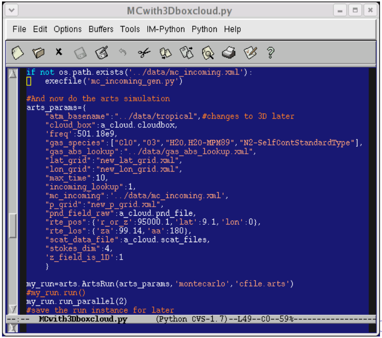
- User can combine a sequence of “workspace methods” (WSM) to perform a variety of tasks e.g. 1D/3D clear/cloudy RT, propagation path calculation, interpolation of atmospheric fields onto new grids,...
- This example performs 3D RT with scattering, using the “MCGeneral” WSM
- MCGeneral has several keyword arguments, most of which determine the termination criteria. desired standard error, maximum time, or number of “photons”.



PyARTS

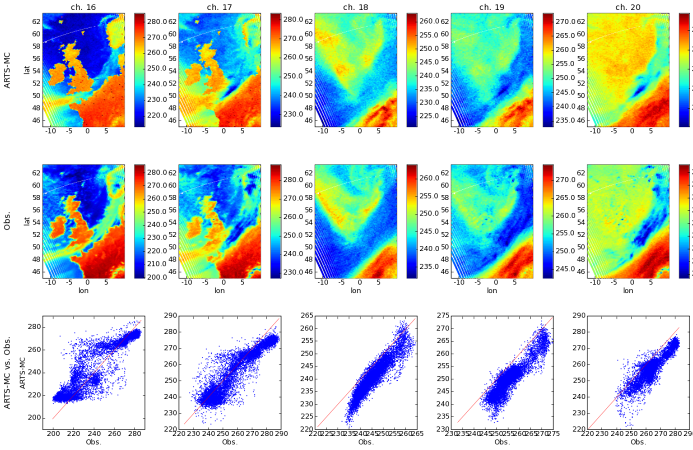
is a python package which: calculates single scattering properties for non spherical hydrometeors (Mishchenko's T-matrix, Warrens REFICE), includes size distributions (e.g. MH 97), prepares everything else needed for ARTS scenarios, and acts as a front-end to ARTS.

- ARTS control files are flexible but not very nice, preceding example > 180 lines
- This PyARTS example calculates scattering properties, creates grids, cloud field, and does MC RT simulation (on 2 processors).
- python => can be used interactively.



AMSU-B simulations

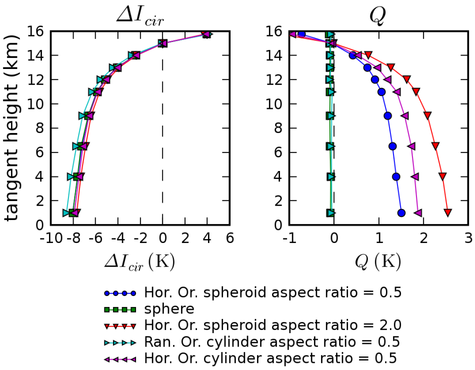
- UM output 220x180x60 grid
- coincident AMSU-B swath
- std err. 1K, 10-30s per pixel
- didn’t realise UM iwc included snow!



Mesoscale model output, and AMSU-B observations provided by Dr. Amy Doherty, MetOffice

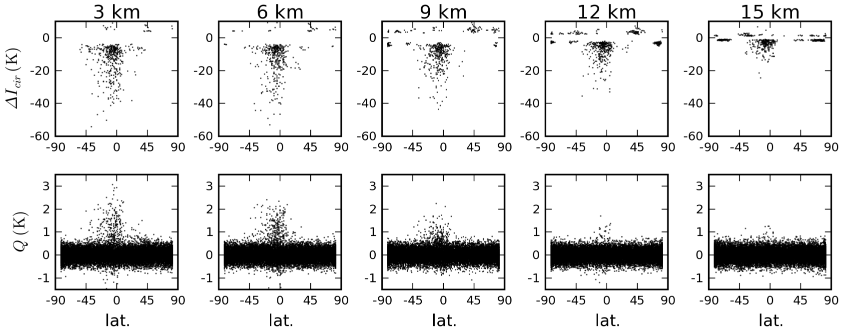
Aura MLS - Polarization

- MLS has both H and V polarizations for R1 (118GHz)
- simple box-shaped simulations show the expected effect of horizontally aligned ice particles on measured **I**
- Horizontally aligned particles give partial vertical polarization (+ive *Q*) with magnitude deceasing with tangent height.



Aura MLS - Polarized observations at 122 GHz

Observations qualitatively similar to simulations - but polarization signal small

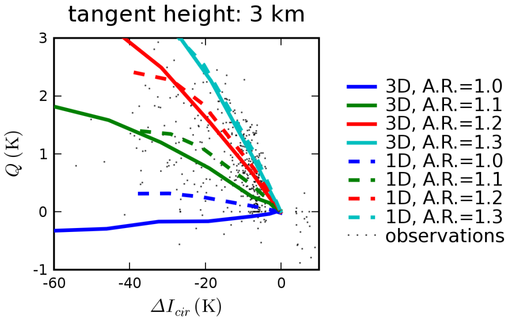


What does this say about shape/orientation?

Aura MLS - Interpretting Polarization

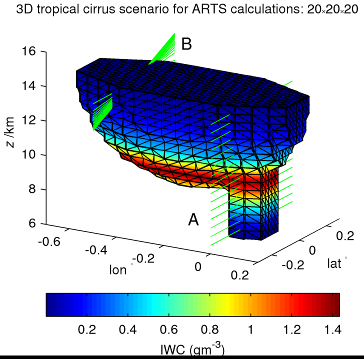
Effect of preferential orientation is mainly determined **in this case** by the ratio $\frac{K_{12}}{K_{jj}}$ and can be replicated by taking a single particle type, horizontally oriented, and modifying the aspect ratio. Easiest to use oblate spheroids.

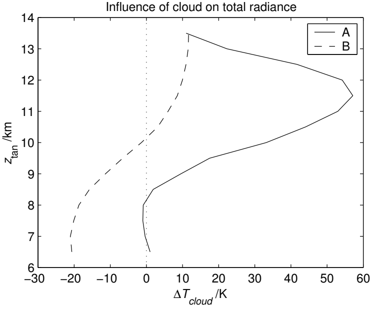
- Comparison with ARTS simulations for 1D and 3D scenarios shows that data is consistent with aspect ratios in the range 1.2 ± 0.15
- Random orientation assumption used in operational retrievals seems OK **for this cloud type**



Aura MLS - 3D effects

IWC retrievals obtain IWC from $\Delta T_{cir} = T_{cloudy} - T_{clear}$, this conversion is based on results from very limited 1D simulations. These 3D simulations show that the use of a 1D model will result in large errors.





Future work

- Use ARTS-MC to improve Aura-MLS cloud products
- Build-up a very large data-set of simulated observations, with a representative distribution of atmospheric scenarios.
- This will allow the trial of different retrieval methods, regression, MCI (Evans), Neural Net.
- More robust cloud products with better error characterisation.

Credits

- ARTS Developers: Stefan Buehler, Patrick Eriksson, Claudia Emde, Oliver Lemke, Sreerekha Ravi,...
- JPL folk: Dong Wu, Jonathan Jiang
- T-matrix: Michael Mishchenko
- Model Validation: Alessandro Battaglia
- UM data: Amy Doherty
- Funding: NERC